Harmonization and intercomparison of CMIP6 climatic models on the marine areas under Spanish jurisdiction

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Abstract: The harmonization of data from numerical models and satellite observations is essential for improving the accuracy of climate projections and supporting informed decision-making. Aligning these sources of information allows for a better integration of projections with observed reality, reducing uncertainties and ensuring that climate change adaptation strategies are based on a more accurate and coherent understanding of current conditions and future expectations. This study explores a simple statistical harmonization for the satellite sea surface temperature (SST) reconstructions using outputs from CMIP6. Our findings highlight the impact of spatial resolution on the ability of climate simulations to represent fine-scale coastal SST variability. High-resolution models better capture interannual changes. These results have implications for climate modeling, coastal process understanding, and regional adaptation strategies.
Keywords: Climate modeling, satellite sea surface temperature, statistical harmonization, reconstruction

SDGs: This work is related to SDGs: 13, 14

I. INTRODUCTION

Climate change and its regional manifestations, particularly in coastal areas, have become a key concern for scientists and policy makers. Sea surface temperature (SST) is one of the most important climate indicators due to its influence on marine ecosystems, coastal economies, and weather patterns. The goal of this work consists of the harmonization and intercomparison of some Coupled Model Intercomparison Project Phase 6 (CMIP6) [1] climate models in the five Spanish marine subdivisions: North Atlantic, South Atlantic, Alboran, Levantine-Balearic and Canary Islands (see FIG. 1). With that, we are going to try to understand how model resolution, particularly the difference between high-resolution and low-resolution variants, affects the fidelity of SST reconstructions when compared to satellite observations.

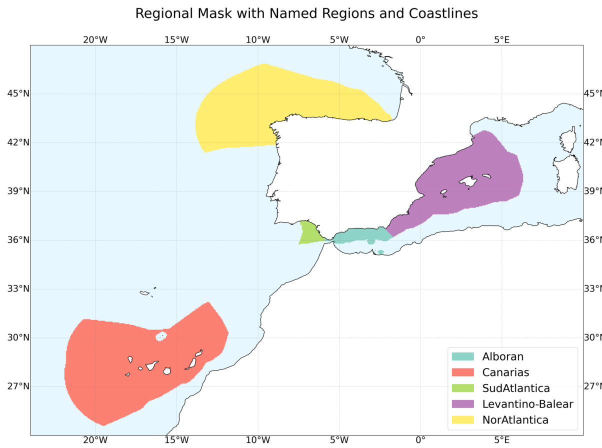

FIG. 1: Region of study: the five Spanish marine subdivisions: North Atlantic, South Atlantic, Alboran, Levantine-Balearic and Canary Islands .

II. DATA AND METHODOLOGY

To assess the ability of climate simulations in reproducing observed coastal SST variability, we analyzed outputs from a subset of CMIP6 models together with satellite-based observations. For that, we compare the temporal evolution and regional patterns of SST in both datasets, and propose a simple harmonization between the outputs of the model and satellite observatiosn, i.e through regression-based methods.

A. Model data

The CMIP6 model data are derived from free-running climate simulations produced by four major modeling centers:

1. Alfred Wegener Institute (AWI)
2. Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)
3. Max Planck Institute (MPI)
4. National Oceanic and Atmospheric Administration (NOAA)

These simulations evolve according to externally imposed radiative forcings (e.g., greenhouse gases, aerosols, solar variability), but do not assimilate observational data. As such, they represent internally generated climate variability and are not synchronized in phase with real-world events. This makes them fundamentally different from reanalysis products, which constrain their evolution through continuous data assimilation. As a result, CMIP6 outputs must be interpreted with care, particularly when comparing against observed time series at regional scales.

The selection of CMIP6 models was based on several criteria to ensure compatibility with satellite observations and internal consistency across model configurations. First, all selected simulations correspond to the historical experiment, which is specifically designed for retrospective evaluation using observed radiative forcings. Unlike future scenario simulations, the historical experiment spans the satellite era. Although these are still free-running simulations and not synchronized with observed internal variability, they are considered the most appropriate CMIP6 experiment for validating past climate behavior.

Among the models that provided data for the SST variable, we prioritized modeling centers that offered paired configurations: one with high nominal spatial resolution and one with lower resolution. This allowed for an analysis of the role of the spatial resolution while keeping model physics and forcing conditions otherwise identical. The selected CMIP6 models are categorized into high- and low-resolution classes. Table I summarizes the nominal and temporal resolution of each model.

Institute	**Model**	**Spatial Resolution**	**Temporal Resolution**
AWI	AWI-CM-1-1-MR	25 km	daily
	AWI-ESM-1-1-LR	50 km	daily
CMCC	CMCC-CM2-HR4	25 km	daily
	CMCC-CM2-SR5	100 km	daily
MPI	MPI-ESM1-2-HR	50 km	daily
	MPI-ESM1-2-LR	250 km	daily
NOAA	GFDL-CM4	25 km	monthly
	GFDL-ESM4	50 km	monthly

TABLE I: Selected CMIP6 models with their spatial and temporal resolution.

B. Observational data

We used the ESA Sea Surface Temperature Climate Change Initiative (SST CCI) version 2.1 [2], which includes both the Climate Data Record (CDR) from the 1980s and its operational extension, the Interim Climate Data Record (ICDR), produced within the Copernicus Climate Change Service (C3S). This Group for High Resolution Sea Surface Temperature (GHRSST) Level-4 dataset provides global, gap-free daily SST fields representative of 20 cm depth, generated by blending multi-sensor satellite observations with in situ data. All files are NetCDF-4 and follow GHRSST metadata standards [3]. These products offer high-quality, gap-filled SST fields, and serve as the reference against which model performance is evaluated. This dataset is provided as GHRSST-compliant Level-4 Climate Data Records (CDRs) in NetCDF-4 format. The ESA SST CCI v2.1 CDR and its near-real-time ICDR extension from C3S are created by optimally blending observations from multiple satellite infrared and microwave sensors, together with in situ measurements, to produce a daily, global, gap-free analysis of SST at approximately 20 cm depth. All files follow variable conventions, making them directly compatible with standard tools (xarray, CDO, etc.) and ideal for rigorous comparison against gridded CMIP6 outputs.

C. Data preprocessing

The preprocessing of SST data across CMIP6 models and satellite observations was a critical step to enable meaningful comparisons. It involved three main stages: spatial cropping, regridding, and temporal alignment.

The first stage consisted of selecting the geographic bounds of the Spanish coastal regions. This step had to account for variations in coordinate names (e.g., `lat`, `latitude`, `nav_lat`) and spatial dimensions (structured vs. unstructured grids). The masking and cropping were applied dynamically using a custom script. The second step was regridding the cropped datasets onto a common regular grid. Here, different techniques were used depending on the structure of the original data. For structured grids, standard linear interpolation (via `scipy.griddata`) was applied [4]. For datasets closer to observational masks, the `xESMF` package provided flexible regridding onto the coastal regions defined by a high-resolution mask file [5].

Finally, temporal alignment ensured all data were expressed as monthly means with timestamps aligned to the 15th of each month. Daily model outputs were averaged to monthly values with standard error propagation. Monthly outputs were shifted in time without further averaging. The satellite data, provided as daily values, were resampled similarly and centered temporally.

All aligned files were saved as NetCDF, keeping attributes and categorizing outputs by model resolution. This multistep data preprocessing was essential to guarantee that intercomparisons and regressions were based on spatially and temporally coherent data, minimizing the effect of biases from irregular sampling or incompatible grid structures.

D. Harmonization

The SST harmonization was performed using the `LinearRegression` class from the `scikit-learn` library in Python [6]. This algorithm fits a multiple linear regression model by minimizing the residual sum of squares between the observed values (satellite SST) and the linear combination of predictors (CMIP6 model outputs). Separate regression models were obtained for the high- and low-resolution ensembles, in each regional time series used as input features. The resulting regression coefficients were then applied to the corresponding model data to harmonize the historical SST evolution over the Spanish marine regions.

III. RESULTS AND DISCUSSION

A. Model overview and SST evolution

Before the models are harmonized we can see a first qualitative comparison between observed and modeled SST without any statistical correction or reconstruction (FIG. 2). Differences in the climatology (bias), seasonal variability, long-term trends, and interannual fluctuations are visible across models and resolutions, reflecting the diversity in model physics and internal variability.

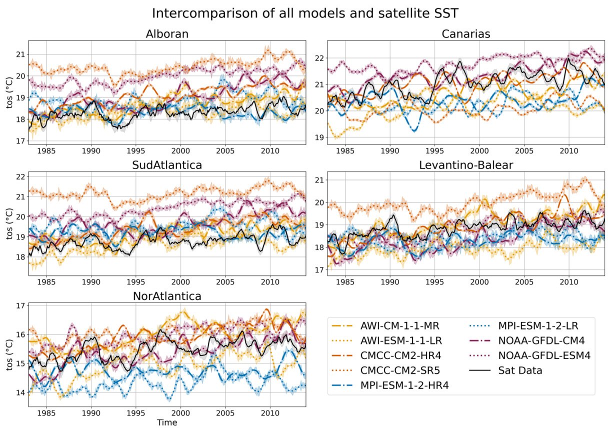

FIG. 2: SST evolution across all CMIP6 models studied and satellite SST data.

The resulting SST time series (FIG. 3) sometimes exhibit low correlation with satellite observations. This indicates that while the absolute differences are small on average, the reconstructed series may not fully capture the temporal variability or structure of the observed SST.

As we can see, the reconstructed series exhibit clear phase shifts or amplitude mismatches relative to the satellite data, especially in the South Atlantic and North Atlantic regions. This suggests that while the linear regression captures the general trend, it may fail to reproduce the timing or intensity of specific SST anomalies.

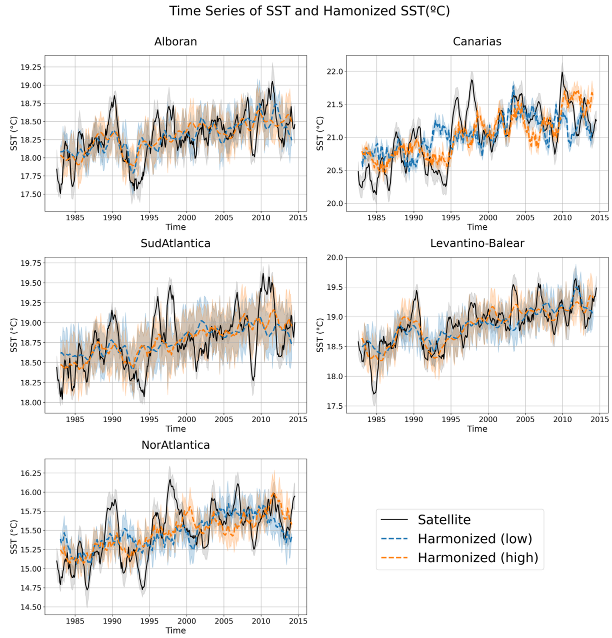

FIG. 3: Intercomparison between the harmonized SST fields for both high and low resolution with the satellite SST.

B. Low-resolution ensemble

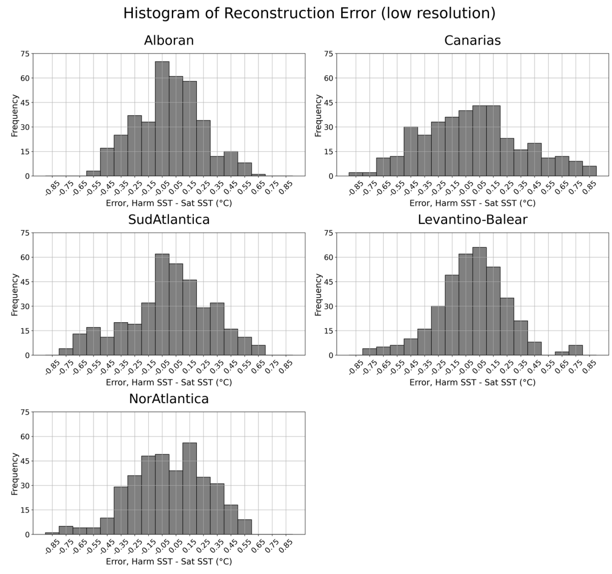

FIG. 4: Histogram of SST errors for low-resolution models.

The low-resolution ensemble demonstrates weaker performance when compared with satellite SST observations. As shown in the error histogram (FIG. 4), the distribution of reconstruction errors is broader and less centered compared to the high-resolution set, indicating greater dispersion relative to satellite observations. In

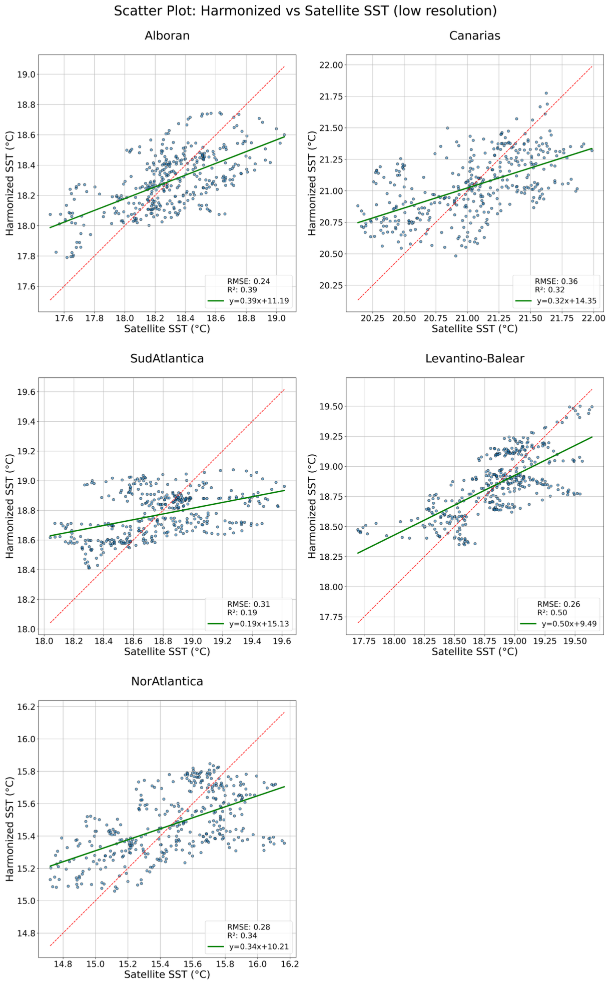

FIG. 5: Scatter plot comparing low-resolution model SSTs with satellite SST observations.

several regions, the error exhibits systematic biases, highlighting the difficulty of accurately capturing interannual fluctuations and coastal thermal anomalies.

These shortcomings are likely due to the coarser spatial resolution, which tends to oversmooth SST gradients and miss key mesoscale processes. Consequently, the reconstructions derived from this ensemble lack the spatial detail needed for accurate coastal climate assessments.

Further supporting this interpretation, the scatter plot (FIG. 5) illustrates that the model outputs are more dispersed, with lower correlation and greater deviation from the identity line. This suggests that low-resolution models struggle to reproduce temporal variability and local SST patterns, especially in narrow coastal regions.

C. High-resolution ensemble

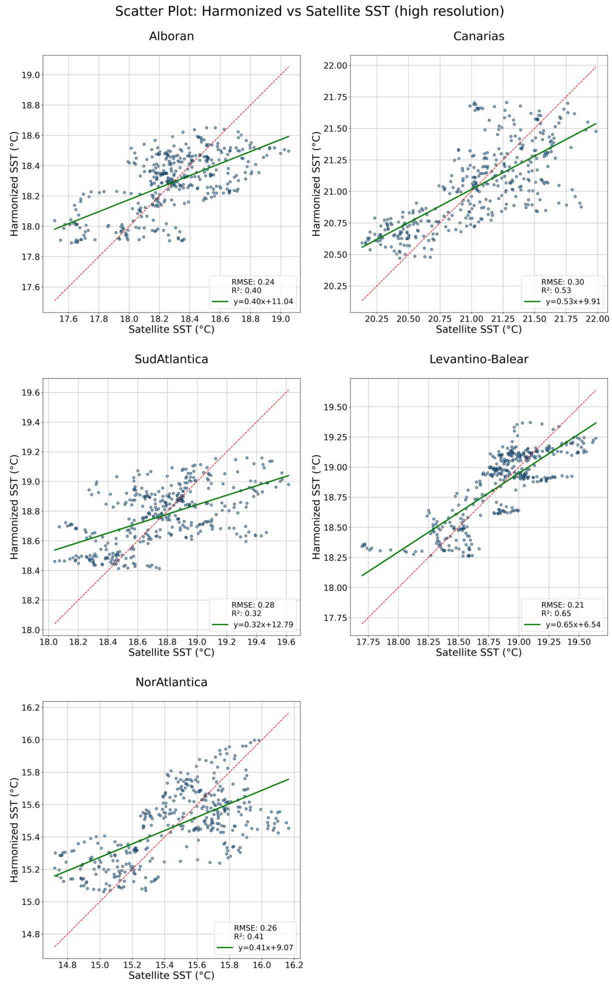

FIG. 6: Scatter plot comparing high-resolution model SSTs with satellite SST observations.

In contrast with the low-resolution group, the high-resolution ensemble shows a stronger correlation with satellite SST observations. This is clearly reflected in the scatter plot (FIG. 6), where most points lie close to the 1:1 line, indicating that these models better capture both seasonal and interannual variabilities with greater fidelity.

Overall, these models benefit from higher spatial resolution, which allows them to resolve finer-scale coastal features such as upwelling and boundary currents. This improves their ability to reproduce SST patterns critical for regional climate analysis.

Complementarily, the error histogram (FIG. 7) for the high-resolution ensemble reveals a narrower distribution centered around zero, supporting the improved agreement with observational data. This suggests that high-resolution models not only better replicate the temporal evolution of SST, but also significantly reduce systematic deviations compared to low-resolution models.

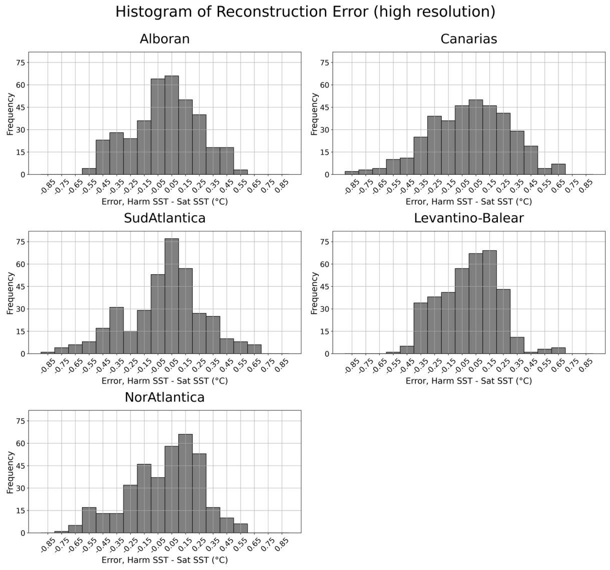

FIG. 7: Histogram of SST errors for high-resolution models.

IV. CONCLUSIONS

This study highlights the importance of model resolution in coastal SST reconstructions. High-resolution CMIP6 models show improved agreement with satellite observations, both in magnitude and variability, while low-resolution models tend to exhibit systematic biases and increased dispersion, especially in narrow coastal zones.

Despite the simplicity of the statistical reconstruction method used, the results underscore how harmonized multi-model ensembles can provide meaningful insights into coastal climate behavior. However, reliance on linear regression may limit the ability to capture more complex or nonlinear SST dynamics, particularly during anomalous events.

Looking ahead, the harmonization and comparison framework presented here can be adapted to other variables and geographic regions. It provides a practical basis for validating climate models in coastal environments and could be extended with more advanced statistical or machine learning methods. This work therefore contributes to improving regional climate assessments and supports the design of more reliable adaptation strategies for oceanic and coastal systems.

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[1] Eyring, V., Bony, S., Meehl, G. A., et al. (2016). *Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization.* Geoscientific Model Development, 9(5), 1937–1958.

[2] European Space Agency (2021). *Sea Surface Temperature Climate Change Initiative (SST CCI) Version 2.1.* Available at: `https://climate.esa.int/en/projects/sea-surface-temperature/` (Accessed May 2025).

[3] GHRSST Project Office, *GHRSST Data Processing Specification (GDS) version 2.0*, 2023. `https://www.ghrsst.org/documents/qcds/` (Accessed: 2025-06-10).

[4] Virtanen, P., Gommers, R., Oliphant, T. E., et al. (2020). *SciPy 1.0: Fundamental algorithms for scientific computing in Python.* Nature Methods, 17(3), 261–272. `https://doi.org/10.1038/s41592-019-0686-2`

[5] Zhuang, J., et al. (2020). *xESMF: Universal Regridder for Geospatial Data.* Available at: `https://xesmf.readthedocs.io` (Accessed May 2025).

[6] Pedregosa, F., Varoquaux, G., Gramfort, A., et al. (2011). *Scikit-learn: Machine Learning in Python.* Journal of Machine Learning Research, 12, 2825–2830.

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Resum: Aquest treball analitza la capacitat dels models climàtics CMIP6 per reproduir l'evolució de la temperatura superficial del mar (SST) en les regions marines sota jurisdicció espanyola. Per fer-ho, s'han utilitzat dades de satèl·lit i simulacions climàtiques lliures d'assimilació d'observacions, provinents de quatre centres de modelització (AWI, CMCC, MPI i NOAA). Posteriorment aquestes dades s'han separat en dos grups, un de models d'alta resolució espacial i un de baixa.

Les dades han estat pretractades per garantir una coherència espaciotemporal: retallades, re-reixades i alineades temporalment en mitjanes mensuals. S'ha aplicat una regressió lineal múltiple per reconstruir l'evolució temporal observada de la SST a partir de les simulacions, avaluant el rendiment de cada grup de models.

Els resultats mostren que els models d'alta resolució capten millor la variabilitat estacional i interanual de la SST, especialment en zones costaneres complexes, mentre que els models de baixa resolució presenten biaixos sistemàtics i dispersió més elevada. Això posa en relleu la importància de la resolució espacial per a la modelització climàtica regional i per a una planificació adaptativa més robusta.

V. OBJECTIUS DE DESENVOLUPAMENT SOSTENIBLE (ODSS O SDGS)

1. Fi de la es desigualtats		10. Reducció de les desigualtats	
2. Fam zero		11. Ciutats i comunitats sostenibles	
3. Salut i benestar	X	12. Consum i producció responsables	
4. Educació de qualitat		13. Acció climática	X
5. Igualtat de génere		14. Vida submarina	X
6. Aigua neta i sanejament		15. Vida terrestre	
7. Energia neta i sostenible		16. Pau, justícia i institucions sólides	
8. Treball digne i creixement económic		17. Aliança pels objectius	
9. Indústria, innovació, infraestructures			

Aquest treball contribueix directament a diversos Objectius de Desenvolupament Sostenible. L'ODS 13 (Acció climàtica) es veu reflectit en la finalitat del projecte: comprendre millor el comportament climàtic regional i aportar eines per a l'adaptació costanera. L'ODS 14 (Vida submarina) està relacionat amb la variable estudiada —la temperatura de la superfície del mar—, que és clau per a la salut dels ecosistemes marins. Finalment, l'ODS 3 (Salut i benestar) s'hi vincula indirectament, ja que els canvis en la temperatura marina poden afectar sectors econòmics com la pesca i, per tant, la seguretat alimentària, així com la propagació de malalties vinculades al clima. Amb aquest estudi es pretén reforçar el coneixement científic necessari per a la presa de decisions fonamentades.

GRAPHICAL ABSTRACT (OPTIONAL)